315-5-1

UNIVERSITY OF ILLINOIS BULLETIN
ISSUED WEEKLY

Vol. XXV May 15, 1928 No. 37

[Entered as second-class matter December 11, 1912, at the post office at Urbana, Illinois, under the Act of August 24, 1912. Acceptance for mailing at the special rate of postage provided for in section 1103, Act of October 3, 1917, authorized July 31, 1918.]

A METALLOGRAPHIC STUDY OF THE PATH OF FATIGUE FAILURE IN COPPER

BY

HERBERT F. MOORE

AND

FRANK C. HOWARD

BULLETIN No. 176
ENGINEERING EXPERIMENT STATION

PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

PRICE: TWENTY CENTS

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Press Notice

To the Editor:

In a separate enclosure I am sending a copy of Bulletin No. 176, entitled "A Metallographic Study of the Path of Fatigue Failure in Copper," by Herbert F. Moore and Frank C. Howard. This bulletin will be issued within the next few days by the Engineering Experiment Station of the University of Illinois. For your convenience a brief review of the bulletin is given below.

If it is consistent with your policy, I shall be glad to receive a copy of your journal containing this notice.

Very truly yours,
M. S. Ketchum, Director

Urbana, Illinois
April, 1928

The study of the failure of metals under repeated stress, commonly known as "fatigue" of metals, has usually been carried on by means of mechanical tests of strength. It has, however, become evident that a study of the nature and mechanism of the progressive fracture which seems to constitute fatigue failure may well employ metallographic examination as an aid in explaining the beginning and the progress of fatigue failure. Such a study of progressive fracture in copper is recorded in Bulletin No. 176 of the Engineering Experiment Station of the University of Illinois.

Copper was chosen as the metal for the metallographic study of fatigue failure largely because it can be obtained in a state of high purity. It was studied cast, rolled and annealed, and rolled, annealed, and then cold drawn.

Among the conclusions drawn were the following:

(1) Specimens of rolled copper, subjected to repeated flexure until a fatigue crack developed, showed a surface disturbance of the metal in the vicinity of the crack. This surface disturbance seems analogous to that found by F. F. Lucas in his study of Armco iron, but is much more clearly marked in the case of rolled cold-drawn copper.

(2) The surface disturbance is shown in micrographs of unetched specimens by lines. The crack as it forms tends to extend parallel to these lines, and the lines seem to develop ahead of the crack, and in the direction which the crack follows as it progresses. Polishing the surface of a specimen removed or covered up all traces of this disturbance.

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UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN NO. 176 MAY, 1928

A METALLOGRAPHIC STUDY OF THE PATH OF FATIGUE FAILURE IN COPPER

BY

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ENGINEERING EXPERIMENT STATION
PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

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A METALLOGRAPHIC STUDY OF THE PATH OF FATIGUE FAILURE IN COPPER

I. Introduction

1. *Introductory.*—The study of the failure of metals under repeated stress, commonly known as "fatigue" of metals, has usually been carried on by means of mechanical tests of strength. It has, however, become evident that a study of the nature and mechanism of the progressive fracture which seems to constitute fatigue failure may well employ metallographic examination as an aid in explaining the beginning and the progress of a fatigue fracture. This bulletin records such a study of progressive fracture in copper.

2. *Acknowledgments.*—Most of the micrographs shown in this bulletin were taken by Mr. K. L. Schanbacher in connection with his bachelor's thesis in chemical engineering, and the writers wish to make a very special acknowledgment to him for his diligence and care in that work.

This study has been carried on as a part of the work of the Engineering Experiment Station of the University of Illinois, and has been under the general administrative direction of Dean M. S. Ketchum, director of the Engineering Experiment Station, and of Professor D. B. Keyes, head of the Division of Applied Chemistry, and Professor M. L. Enger, head of the Department of Theoretical and Applied Mechanics.

II. Metallographic Study of Fatigue Failure in Copper

3. *Previous Metallographic Studies of Fatigue Cracks.*—Various investigators have taken micrographs of fatigue cracks and Mr. F. F. Lucas, Metallurgist of the Bell Telephone Laboratories, New York, has made a very careful study of the path of fatigue failure in Armco iron.*

In his investigation of the path of fatigue failure, with magnifications ranging from 100 to 4800, he found that in the case of Armco iron:

> "1. Non-metallic inclusions in Armco iron are a potential source of weakness when such metal is subjected to reversed cycles of stress.

*Lucas, F. F., "Observations on the Microstructure of the Path of Fatigue Failure in a Specimen of Armco Iron," Trans. Am. Soc. for Steel Treating, April, 1927.

"2. Iron carbide when occurring as inclusions in Armco iron is not a source of weakness.

"3. Non-metallic inclusions seem to be insecurely seated in the metal and the boundary between the inclusion and the metal is the path often followed by the fatigue crack.

"4. The non-metallic inclusions act as 'stepping-stones' for the fatigue crack.

"5. Grain boundaries do not appear to be a potential source of weakness.

"6. Reversed cycles of stress appear to produce disturbances in the structure of the metal in advance of the visible crack, as disclosed by light etching. This condition at times can be disclosed by deeper etching.

"7. Disturbances in the metal structure adjoining the path of fatigue failure seem to be highly localized to the immediate neighborhood of the crack.

"8. Slip planes, strain lines, Neumann bands or other similar markings were not found if the strained condition of the metal immediately adjoining the crack is disregarded."

4. *Material Studied.*—Copper was chosen as the metal for a metallographic study of fatigue failure largely because it can be obtained in a state of high purity. It was studied cast, rolled and annealed, and rolled, annealed, and then cold drawn. The cast copper was furnished by the Western Electric Company and is their commercially pure cast copper. The rolled copper was furnished by the Bridgeport Brass Company. The chemical content of the two lots of copper was as follows:

Rolled and Annealed Copper Also Cold-drawn Copper from Bridgeport Brass Co.

Copper	99.895 per cent
Carbon	nil
Iron	nil
Manganese	nil
Phosphorus	nil
Sulphur	nil
Aluminum	nil
Zinc	nil
Lead	nil
Tin	nil
Oxygen and Copper Oxide	0.105 per cent

Cast Copper from Western Electric Co.

Copper and Silver	99.91 per cent
Silver	0.006 per cent
Lead	0.01 per cent
Electrical Conductivity (International Standard)	100.1

The rolled and annealed and the cold-drawn copper were given the following mechanical treatments at the works of the Bridgeport Brass Company:

Rolled and annealed copper: extruded at 1380° F. to 1 inch round; pickled and washed; drawn to ⅞ inch round; annealed at 1290° F. in oxidizing atmosphere for 30 min.; pickled and washed; drawn cold to ¾ inch round; annealed for 30 min. at 1290° F. in oxidizing atmosphere; pickled and washed.

Cold-drawn copper: treated as above, then cold drawn to ½ inch diameter in one operation.

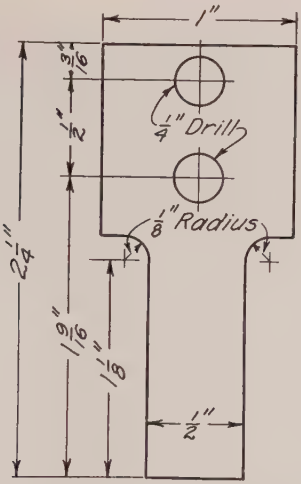


FIG. 1. SPECIMEN USED IN REPEATED-STRESS TESTS

5. *Apparatus and Specimens for Developing Fatigue Crack.*—The test specimens in which fatigue cracks were developed are shown in Fig. 1. The specimen was clamped at its upper end and the lower end was bent back and forth in a plane perpendicular to the plane of the paper. The points of maximum bending stress were at the junction of fillet (⅛-inch radius) and the narrower part of the specimen. Figure 2 shows a specimen with a fatigue crack in it. Figure 3 shows the testing machine used to subject the specimen to cycles of repeated stress. The specimen N is fastened at one end to the calibrated spring M and the other end is vibrated back and forth by the connecting rod K, which is operated by the variable-throw crank D. If the throw of the crank D is increased, the bending moment is increased, and the deflection of Q, a concave mirror attached to the calibrated spring, is increased, causing a motion of the ray of light reflected from the lamp L to the screen S. The image of a filament of the lamp is focussed at S. The length of the band of light, reflected on the screen S as the machine runs, is a measure of the bending moment, and hence of the range of flexural stress in the specimen. A counter is provided to measure the number of cycles of stress applied.

6. *Procedure in Etching Specimens.*—Each specimen studied was polished over the surfaces near the fillets, using Nos. 1 to 0000 emery paper and, finally, jeweler's rouge. Various etching solutions were tried to bring out the microstructure of the copper. Some etching

FIG. 2. MACROGRAPH OF FATIGUE CRACKS IN COLD-DRAWN COPPER SPECIMEN (x 3.5)

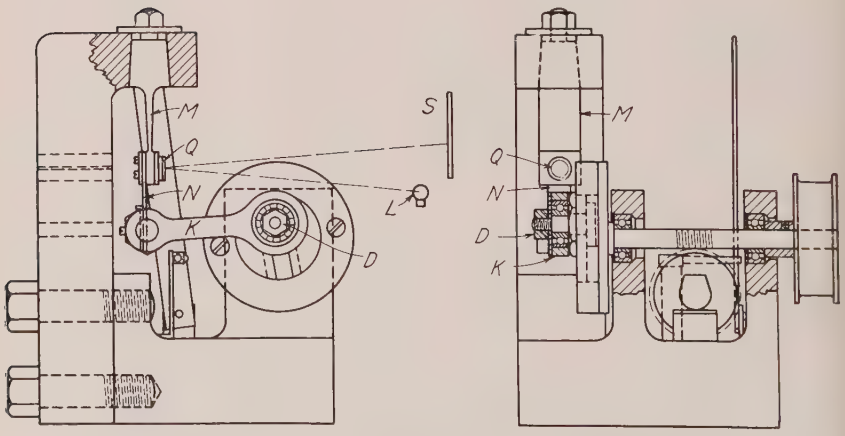


FIG. 3. TESTING MACHINE USED FOR REPEATED-STRESS TESTS

FIG. 4. MICROGRAPH OF DRAWN AND ANNEALED COPPER (x 840)
Etched with concentrated nitric acid.
H—"Herringbone" structure; L—"Laminated" structure; M—"Mottled" structure.

solutions recommended in Bureau of Standards Scientific Paper S 399 were tried, as was ammoniacal hydrogen peroxide, followed by a dip in concentrated nitric acid, as recommended by Pulsifer.* However, the most satisfactory procedure in etching was found to consist in merely dipping the specimen in concentrated nitric acid and removing it as soon as the oxides of nitrogen began to be evolved. This procedure was followed for nearly all the specimens studied.

7. *Procedure in Developing a Fatigue Crack.*—The endurance limit for pure copper either rolled and annealed or cold drawn is approximately 10 000 lb. per sq. in.† Fatigue cracks were developed by subjecting specimens to 250 000 cycles of a reversed flexural stress of 15 000 lb. per sq. in. This procedure developed a fatigue crack in each specimen tested (see Fig. 2), but did not cause complete fracture.

8. *Structure of Specimens Before Being Subjected to Repeated Stress.*—The appearance of the annealed copper before being stressed is shown in Fig. 4. It is noted that there are three types of structure vis-

*Pulsifer, H. B., "Microscopic Structure of Copper," Mining and Metallurgy, January, 1926.
†See Univ. of Ill. Eng. Exp. Sta. Bul. 152, p. 58.

FIG. 5. MICROGRAPH OF COLD-DRAWN COPPER, LONGITUDINAL SECTION (x 400)
Etched with concentrated nitric acid.
H—"Herringbone" structure; L—"Laminated" structure; M—"Mottled" structure.

ible which, from their appearance, may be designated as "laminated," "herring-bone," and "mottled," respectively. The same varieties of structure were exhibited by the cold-drawn copper before being subjected to repeated stress, as shown in Fig. 5. It is noted that the grains in this case were very much elongated in the direction of drawing due to the mechanical work. The transverse section of cold-drawn copper, shown in Fig. 6, does not show this elongation of the grains but the grains are very much smaller and the structure apparently somewhat finer in some of the grains than is the case along longitudinal sections. It may also be noted that some of the grains are not in the same plane as the surface of the specimen, and this is shown in the micrograph by a decided blurring of the edges.

A micrograph with a magnification of 11 500 diameters was obtained for one of the mottled grains and is shown in Fig. 7a. If the herring-bone structure (e.g. at H Fig. 4) is due to the action of the nitric acid on the material between or along cleavage planes, then apparently Fig. 7a shows a grain that has begun to break up along planes at right angles to the main cleavage planes. This,

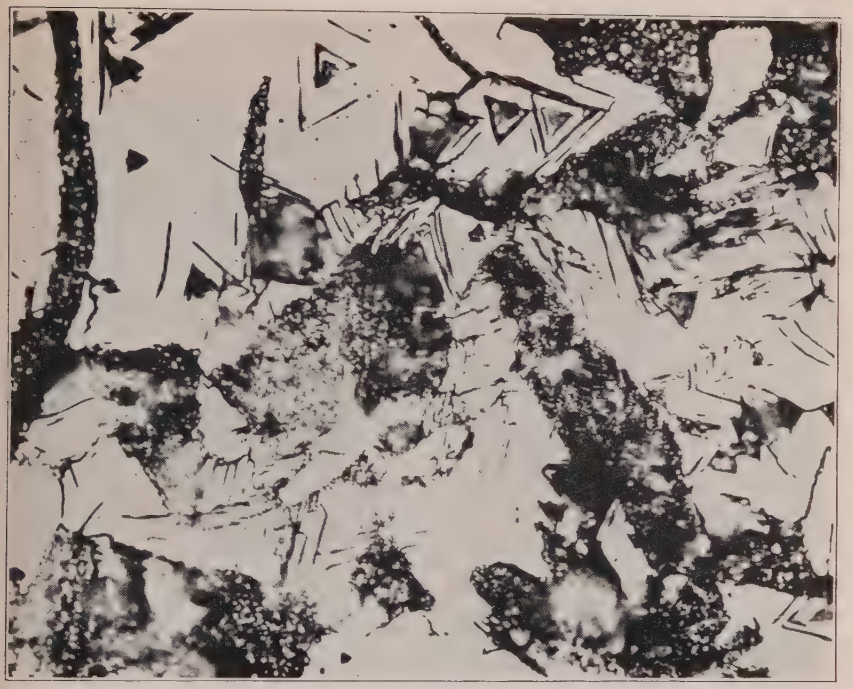


FIG. 6. MICROGRAPH OF COLD-DRAWN COPPER, TRANSVERSE SECTION (x 1300)
Etched with concentrated nitric acid.

therefore, would seem to indicate not only that there is a set of secondary cleavage planes at right angles to the primary cleavage planes but also that in this particular case the annealing not only failed to remove the evidences of strain within the crystal but also failed to "heal" a grain that had started to disrupt.

The distance between the laminated or parallel lines in the micrographs (Figs. 4, 7, 18, and 19) can be measured and then the corresponding distance in the specimen can be calculated. It was found that this distance varied from 0.0004 to 0.001 millimeters. These distances are well within the theoretical resolving power of the objectives used. The theoretical resolving power is the smallest distance that may be resolved optically; or $d = \frac{\lambda}{2a}$ where λ = the wave length of light used in mm., a = numerical aperture, d = the smallest resolvable distance in mm. A Bausch and Lomb green filter was used in this work so that $\lambda = 0.00053$ mm.; for the oil immersion objective $a = 1.3$,

FIG. 7a. HIGH-MAGNIFICATION MICROGRAPH OF ANNEALED COPPER (X 11 500)
Etched with concentrated nitric acid. "Mottled" crystalline grain.

FIG. 7b. HIGH-MAGNIFICATION MICROGRAPH OF ANNEALED COPPER (× 11 500)
Etched with concentrated nitric acid. Homogeneous crystalline grain

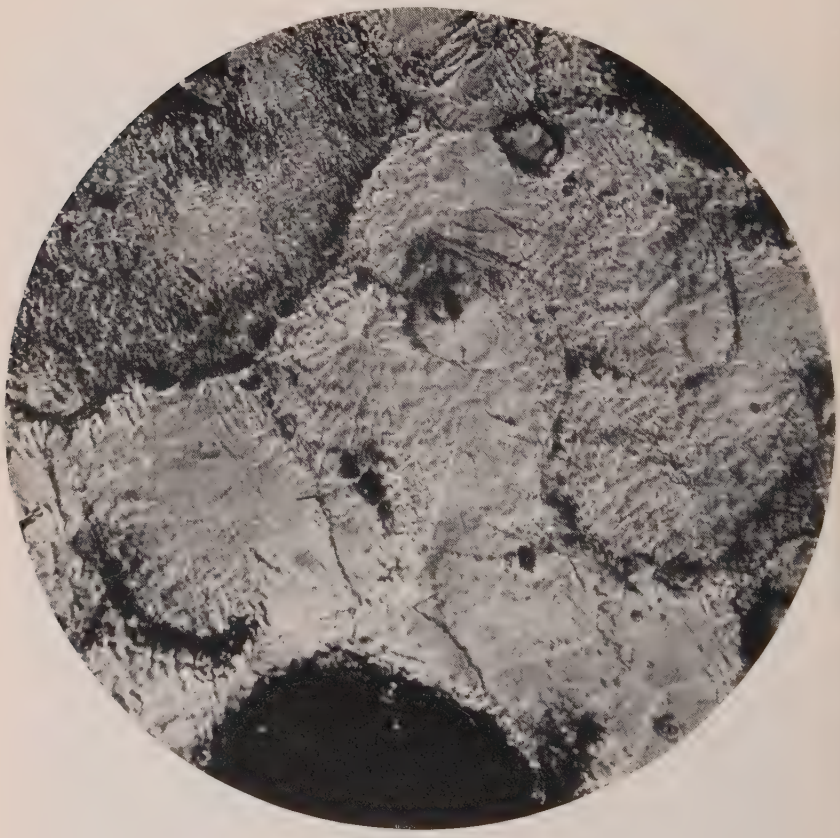
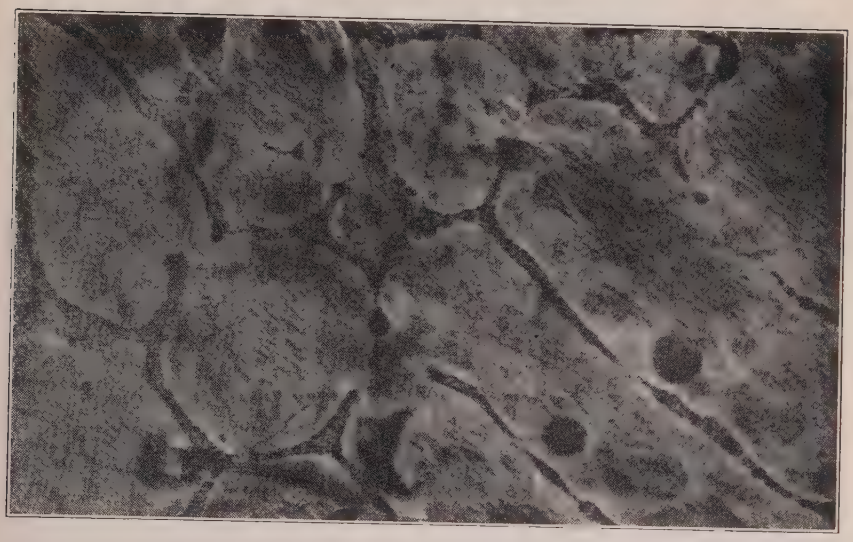


FIG. 8. MICROGRAPH OF CAST COPPER (x 800)
Etched with concentrated nitric acid.

therefore $d = \frac{0.00053}{2 \times 1.3} = 0.0002$ mm.

Figure 8 shows the structure of a piece of the same copper as shown in Figs. 4 and 5 after being remelted and cast into a mold. The laminated and herring-bone structures seem to be absent in this case; however, in Fig. 9 are shown micrographs of cast copper supplied by the Western Electric Company. The specimen 9b was taken from near the edge of the ingot. The appearance of the micrograph suggests a very fine laminated structure within the grain. Figure 8 shows a micrograph of cast copper taken from the interior of an ingot; no evidence of laminated structure is shown, and this was typical of all specimens of cast copper or cast alloys of copper (other than that shown in Fig. 9b) which have been examined by the writers.



a

From interior of ingot. Etched with concentrated nitric acid (x 400).

b

From near edge of ingot (different copper from that shown in Fig. 9a). Etched with concentrated nitric acid (x 1300).

FIG. 9. MICROGRAPHS OF CAST COPPER

FIG. 10. MICROGRAPH OF FATIGUE CRACK IN ROLLED AND ANNEALED COPPER (X 100)
Unetched.

The laminated structures, herring-bone structures, and, perhaps, the mottled structure found in the unstressed copper seem to show planes within crystalline grains which are particularly susceptible to chemical attack. Whether these planes are also indicators of structural weakness is an interesting question on which a little light is thrown by the results of the repeated stress tests. It would be very interesting to find out whether these planes that are susceptible to chemical attack bear any relation to the characteristic planes of the space lattice of copper, but the writers have no data to offer on that question.

9. *Structure of Copper in the Vicinity of a Fatigue Crack.*—Figures 10, 11, 12, and 13 are micrographs of unetched specimens taken so as to show a fatigue crack developed as described on page 9. Figure 10 is a micrograph of annealed drawn copper; Fig. 11 is a micrograph of cold-drawn copper; Fig. 12 is a micrograph of cold-drawn copper repolished after the development of the fatigue crack; and Fig. 13 is a micrograph of cast copper from the Western Electric Co.

Lucas in his study of fatigue cracks in Armco iron reported a "disturbed region" round the crack. Figures 10 and 11 show such a

disturbed region very plainly for the drawn and annealed, and the cold-drawn copper. Figure 12 is interesting as showing that the evidences of the disturbed area are removed by repolishing. Figure 13, showing a fatigue crack in cast copper, gives little evidence of a disturbed region around the crack. This is in accord with the evidence shown by micrographs of copper etched after the development of a fatigue crack.

In Figs. 14 and 15 a general tendency towards parallelism between crack and disturbance lines is noted, while Figs. 15 and 16 show disturbance lines apparently acting as advance agents for the progress of the crack. Figure 17 shows disturbance lines in drawn and annealed copper.

Figures 18 and 19 are micrographs showing the appearance of cold-drawn copper in the vicinity of a fatigue crack after the surface of the metal had been etched with concentrated nitric acid. The disturbed region around the crack is less clearly marked than was the case for the unetched surfaces shown in Figs. 10 to 17, inclusive, and is shown as an out-of-focus blurred region at the edge of the crack. The crystalline structure of the copper is similar to that shown in Fig. 5, and no change in that structure is apparent. In certain places there seems to be a tendency for the crack to follow a path parallel to the laminae of the grains, but at other places the crack goes across these laminae.

To the writers a study of Figs. 10 to 18, inclusive, suggests the following picture of the origin and spread of a fatigue crack in copper: The crack originates in surface disturbances such as are shown in Figs. 15 and 16. Once the crack is started it spreads inwards and also along the surface, the major factor governing its spread being the stress concentration at its edges, and a minor factor being local planes of weakness in different crystalline grains. The copper tested was almost free of inclusions; in Fig. 16 the incipient crack C is seen passing at the edge of an inclusion, as was frequently found by Lucas in his study of Armco iron. In general, however, the inclusions are so few, except possibly in the case of cast copper, and so widely scattered that they do not affect the path of the crack in the copper specimens studied.

III. Conclusions

10. *Conclusions.*—As a result of the investigation the following conclusions are given:

(1) By etching with concentrated nitric acid there was brought out in the rolled copper tested an intra-granular structure consisting of laminae separated by planes especially sensitive to chemical attack. This structure was brought out in one specimen of cast copper tested.

(2) Specimens of rolled copper, subjected to repeated flexure until a fatigue crack developed, showed a surface disturbance of the metal in the vicinity of the crack. This surface disturbance seems analogous to that found by Lucas in Armco iron, but is much more clearly marked in the case of rolled cold-drawn copper.

(3) The surface disturbance is shown in micrographs of unetched specimens by lines. The crack as it forms tends to extend parallel to these lines, and the lines seem to develop ahead of the crack, and in the direction which the crack follows as it progresses. Polishing the surface of a specimen removed or covered up all traces of this disturbance.

(4) The rolled copper tested had in it so few inclusions that any tendency of the crack to take a course from inclusion to inclusion was not in evidence.

(5) Specimens of rolled copper etched after the development of a fatigue crack showed no evidence of any change in crystalline structure, and after the surface had been eaten away by the etching reagent the disturbed region in the vicinity of the crack was much less in evidence than on the unetched surface.

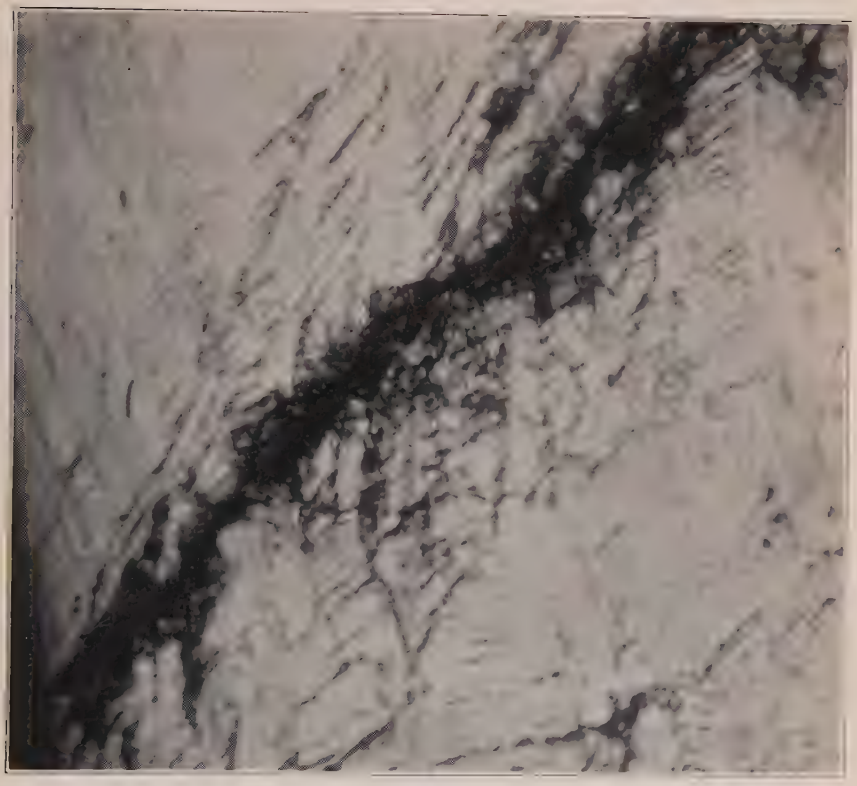


FIG. 11. MICROGRAPH OF FATIGUE CRACK IN COLD-DRAWN COPPER (x 100)
Unetched.

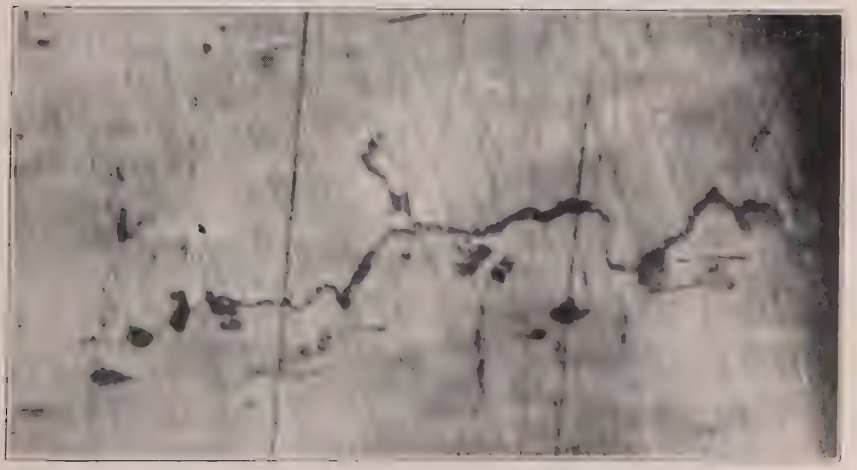


FIG. 12. MICROGRAPH OF FATIGUE CRACK IN COLD-DRAWN COPPER. REPOLISHED AFTER DEVELOPMENT OF CRACK (x 100)

FIG. 13. MICROGRAPH OF FATIGUE CRACK IN CAST COPPER (X 800)
Unetched.

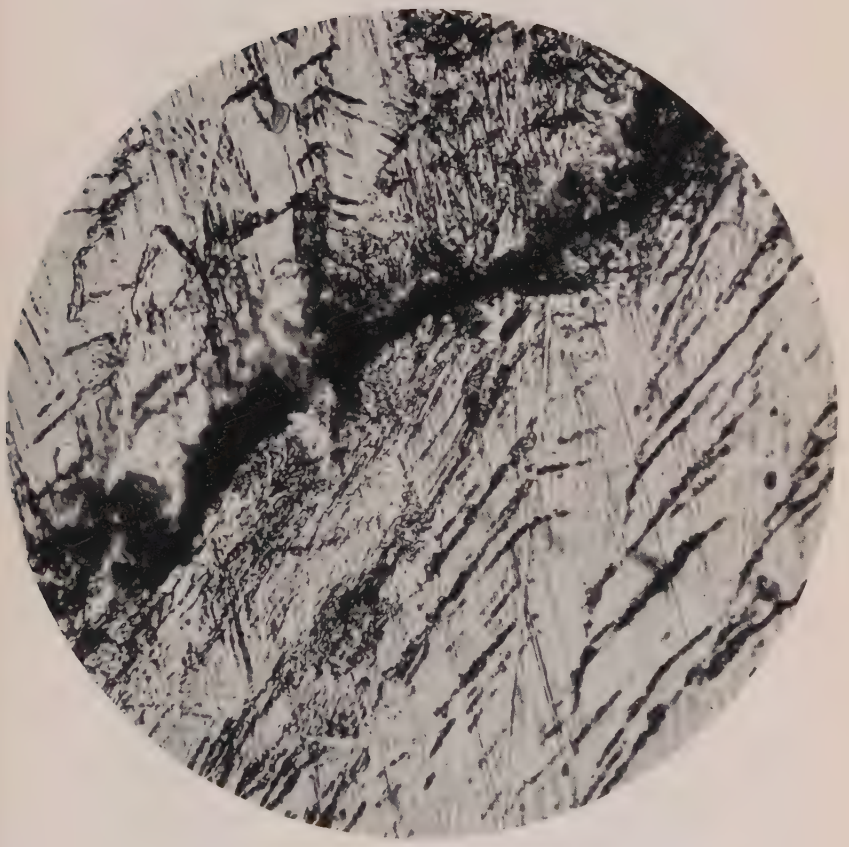


FIG. 14. MICROGRAPH OF DISTURBANCE LINES AROUND FATIGUE CRACK IN COLD-DRAWN COPPER (X 800)
Unetched.

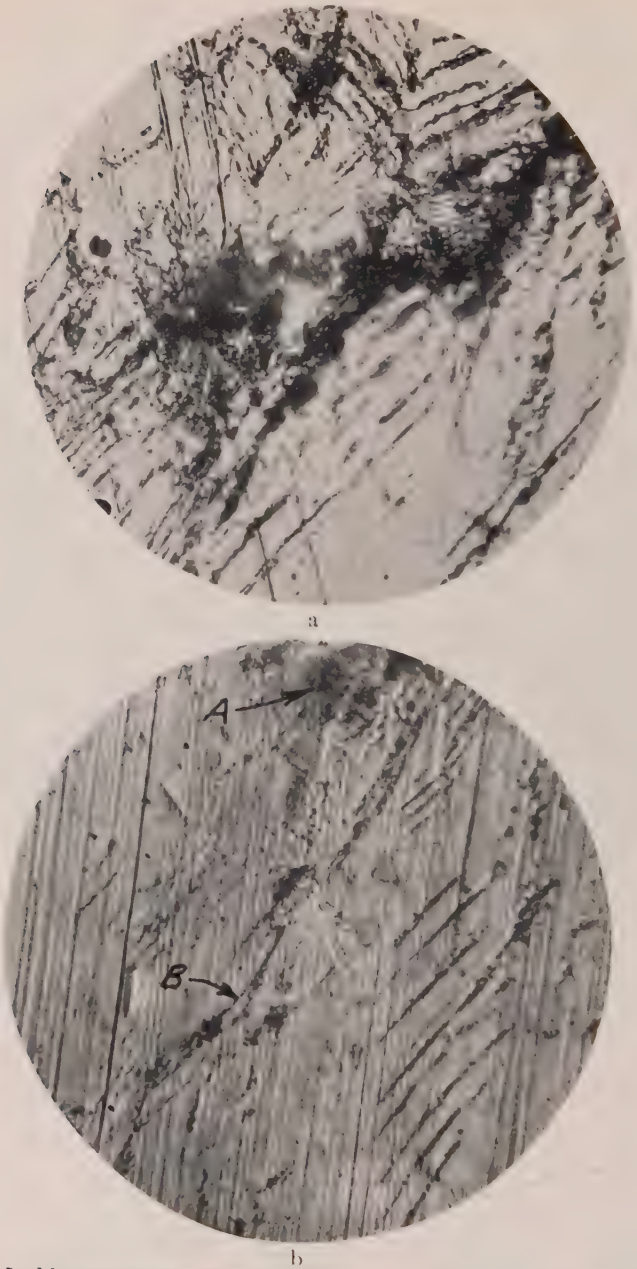


FIG. 15. MICROGRAPHS OF DISTURBANCE LINES AROUND AND AHEAD OF FATIGUE CRACKS IN COLD-DRAWN COPPER (X 800)

Unetched.

A, end of a crack; B, incipient crack.

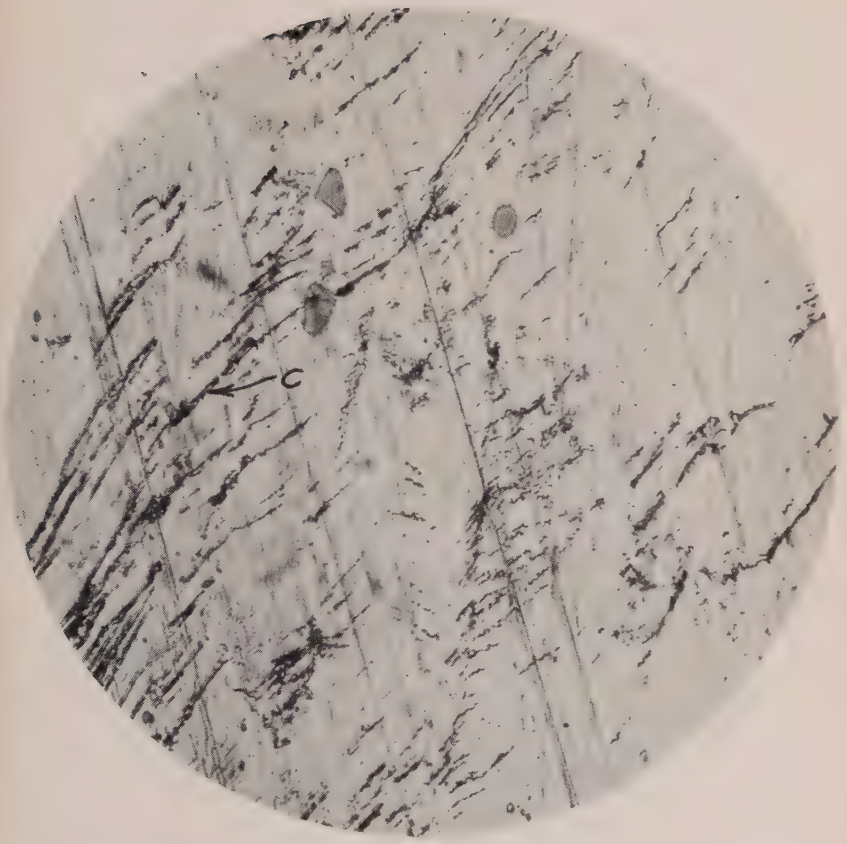


FIG. 16. MICROGRAPH OF SURFACE DISTURBANCE LINES SHOWING POSSIBLE FORMATION OF FATIGUE CRACK IN COLD-DRAWN COPPER (x 800)
Unetched. C, incipient crack.

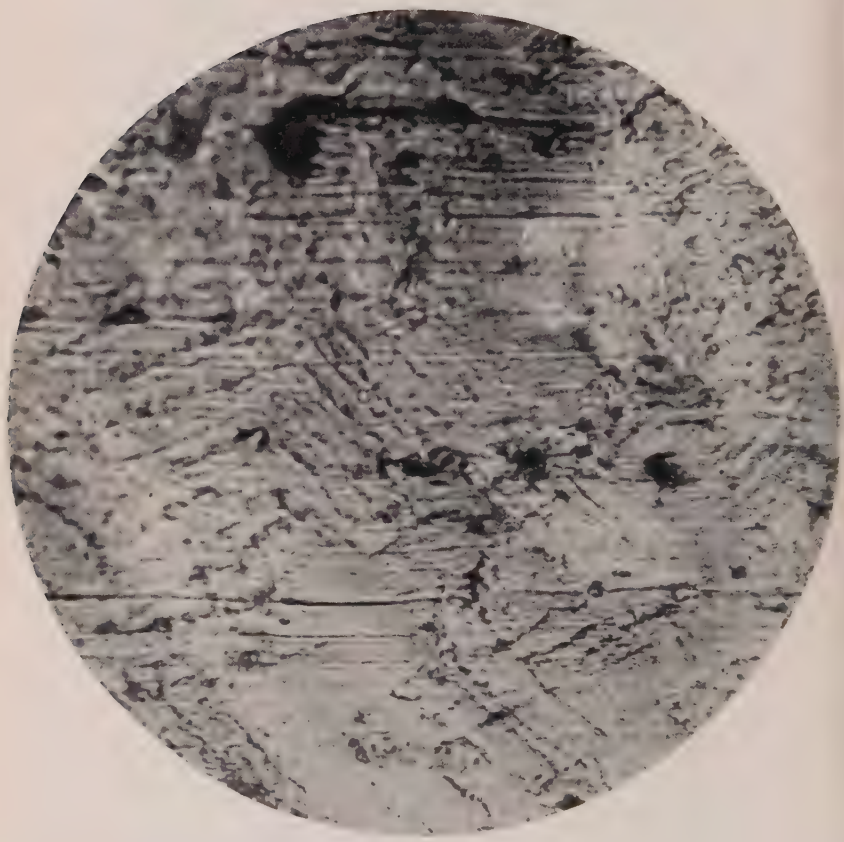


FIG. 17. MICROGRAPH OF DISTURBANCE LINES AHEAD OF A FATIGUE CRACK IN ROLLED AND ANNEALED COPPER (X 800)
End of crack not in field of view. Unetched.

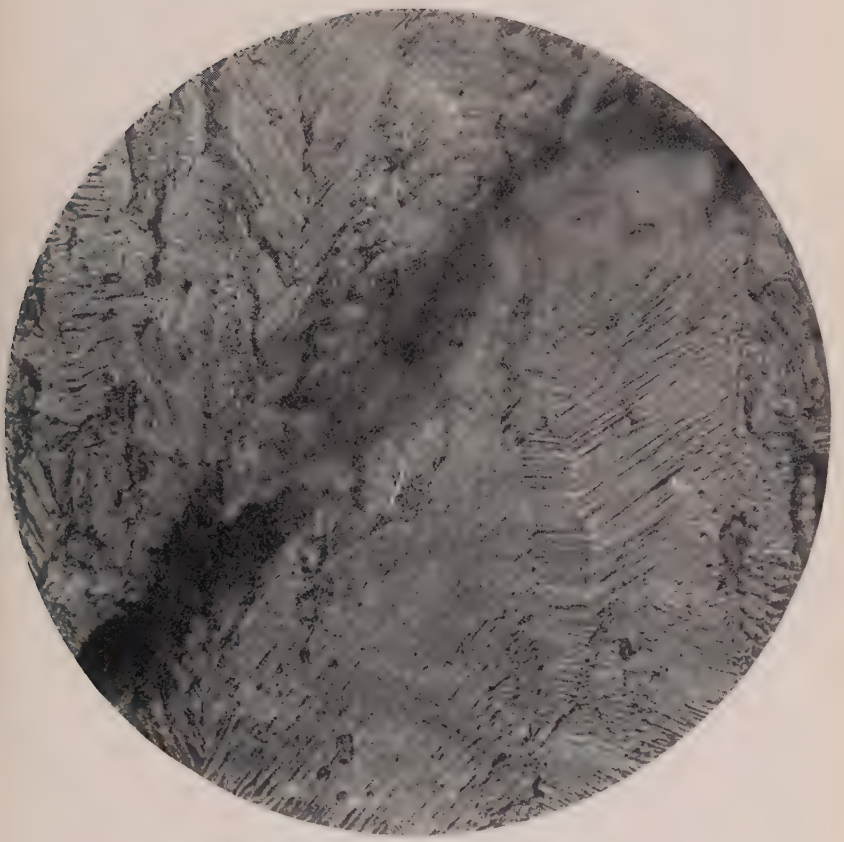


FIG. 18. MICROGRAPH OF FATIGUE CRACK IN COLD-DRAWN COPPER (x 800)
Etched with concentrated nitric acid.

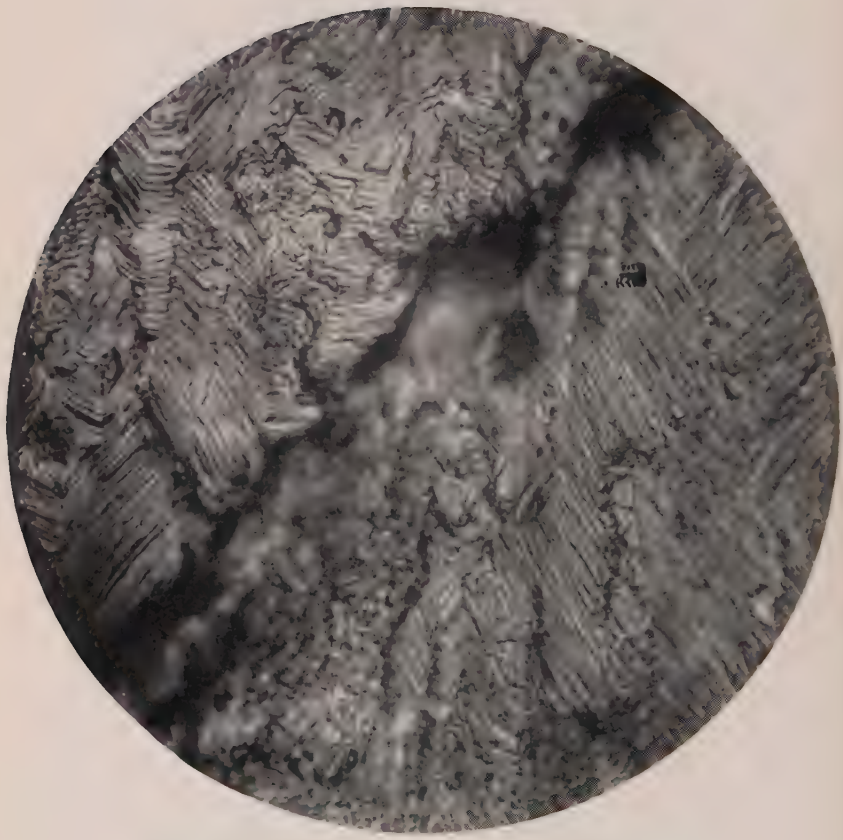


FIG. 19. MICROGRAPH OF FATIGUE CRACK IN COLD-DRAWN COPPER (x 800)
Etched with concentrated nitric acid.

FIG. 20. MICROGRAPH OF FATIGUE CRACK IN CAST COPPER (x 800)
Etched with concentrated nitric acid.

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